

Sensitivities of IceCube DeepCore Detector to Signatures of Low-Mass Dark Matter in the Galactic Halo

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Abstract

We discuss the event rate in DeepCore array due to neutrino flux produced by annihilations and decays of galactic dark matter. This event rate is calculated with a 10 GeV threshold energy, which is smaller than the threshold energy taken in previous works. Taking into account the background event rate due to the atmospheric neutrino flux, we evaluate the sensitivity of DeepCore array for probing dark matter annihilation cross section and decay time. The sensitivity studies include the annihilation modes $\chi\chi \rightarrow b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, and $\nu\bar{\nu}$, and decay modes $\chi \rightarrow b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, and $\nu\bar{\nu}$. We compare our results with corresponding constraints derived from observations of WMAP, ACT and Fermi-LAT.

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I. INTRODUCTION

Many astrophysical observations indicate the existence of dark matter (DM). A good example of such observations is the measurement of rotation curves for stars and gas in spiral galaxies. On the other hand, the nature of DM remains to be unveiled. In this regard, many DM candidates have been proposed with the proposal of weak interacting massive particles (WIMPs) [1, 2] the most popular among all candidates. The detections of DM shall test the idea of WIMPs. The detections of DM can be categorized into direct and indirect approaches. The former approach proceeds by observing the nucleus recoil as DM interacts with the target nuclei in the detector. The latter approach relies on detecting final state particles resulting from DM annihilations or decays. In this article, we focus on the indirect detection of DM through observing neutrinos produced by DM annihilations or decays in the galactic halo.

The search for neutrinos coming from DM annihilations in galactic halo has been performed by IceCube [3]. Data obtained from IceCube 22-string configuration set the 90% C.L. upper limit on DM annihilation cross section $\langle\sigma v\rangle \sim 10^{-22}\text{cm}^3\text{s}^{-1}$ for $\chi\chi \rightarrow \nu\bar{\nu}$ channel at $m_\chi = 1\text{ TeV}$ [4], while the preliminary result of IceCube 40-string galactic-center analysis improves the above limit to $10^{-23}\text{cm}^3\text{s}^{-1}$ [5]. Based upon IceCube 40-string data selection for searching diffuse flux of astrophysical muon neutrinos [6], a comparable constraint on the cross section of $\chi\chi \rightarrow \nu\bar{\nu}$ annihilations, which could take place in the core of Earth, is derived [7] for TeV range dark-matter masses. Furthermore, upper limits on the annihilation cross sections of $\chi\chi \rightarrow \mu^+\mu^-$ and $\chi\chi \rightarrow \tau^+\tau^-$ channels are also obtained. It is interesting to compare these upper limits with the required annihilation cross sections for the same channels for explaining the PAMELA data on positron fraction excess [8] and Fermi-LAT $e^+ + e^-$ fluxes measurement [9]. As shown in Ref. [4], the IceCube upper limit on $\chi\chi \rightarrow \tau^+\tau^-$ annihilation cross section is comparable to the required $\chi\chi \rightarrow \tau^+\tau^-$ annihilation cross section for explaining PAMELA and Fermi-LAT data. On the other hand, the IceCube upper limit on $\chi\chi \rightarrow \mu^+\mu^-$ annihilation cross section is still too high to test the idea of using this mode to account for PAMELA and Fermi-LAT data.

The IceCube sensitivity on DM search is expected to improve with the data from all 86 strings analyzed. The analysis of DeepCore array data will further enhance the sensitivity. The DeepCore array [10–12] is located in the deep center region of IceCube detector. This

array consists of 8 densely instrumented strings plus the nearest standard IceCube strings. The installation of DeepCore array significantly improves the rejection of downward going atmospheric muons in IceCube and lowers the threshold energy for detecting muon track or cascade events to about 5 GeV. This muon rejection is crucial for IceCube to observe DM induced neutrino signature from galactic halo. In fact, it has been pointed out that the parameter range for $\chi\chi \rightarrow \mu^+\mu^-$ channel preferred by PAMELA and Fermi-LAT data could be stringently constrained [13–15](see also discussions in Ref. [16]) by the data from IceCube detector augmented with DeepCore array. In this work, we shall however focus on the low-mass DM instead of DM with its mass in the range preferred by PAMELA and Fermi-LAT.

We note that previous analyses on DeepCore sensitivity [15, 17] have set the threshold energy at (40 – 50) GeV for both track and cascade events. However, to take the full advantage of DeepCore array, it is desirable to include neutrino events in the energy range $10 \text{ GeV} \leq E_\nu \leq 50 \text{ GeV}$. We have initiated such a study for track events [18]. In this work, we generalize the previous study to cascade events in IceCube DeepCore detector. Since we are only interested in low-mass DM, we only consider channels $\chi\chi \rightarrow b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, and $\nu\bar{\nu}$ for annihilations and channels $\chi \rightarrow b\bar{b}$, $\tau^+\tau^-$ and $\mu^+\mu^-$, and $\nu\bar{\nu}$ for decays. The neutrino fluxes generated through DM annihilations or decays into $t\bar{t}$, W^+W^- and ZZ final states are not included in this analysis.

This paper is organized as follows. In Sec. II we describe neutrino fluxes from DM annihilation/decay at the galactic halo for different halo profiles. In Sec. III we briefly describe our results on the background atmospheric neutrino fluxes taking into account neutrino oscillations. In Sec. IV we present our results on the projected five year sensitivity of DeepCore array on cascade events induced by DM annihilations and decays. In addition, we shall also compare our results with the up-to-date indirect detection limits from Fermi-LAT gamma ray data and cosmic microwave background (CMB) observations. Specifically, we shall compare the DeepCore sensitivities on DM annihilation cross section $\langle\sigma v\rangle$ and DM decay time with corresponding constraints obtained from gamma ray observations [19, 20](see also analysis in Ref. [21]) and those obtained from CMB anisotropy [22, 23] based on one or both of the recent WMAP 7-year [24] and ACT 2008 [25] data. Discussions and conclusions are given in Sec. V.

II. NEUTRINO FLUX FROM ANNIHILATIONS AND DECAYS OF DARK MATTER IN THE GALACTIC HALO

The differential neutrino flux from the galactic dark matter halo for neutrino flavor i can be written as [26]

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{\Delta\Omega}{4\pi} \frac{\langle\sigma v\rangle}{2m_\chi^2} \left(\sum_F B_F \frac{dN_{\nu_i}^F}{dE} \right) R_\odot \rho_\odot^2 \times J_2(\Delta\Omega) \quad (1)$$

for the case of annihilating DM, and

$$\frac{d\Phi_{\nu_i}}{dE_{\nu_i}} = \frac{\Delta\Omega}{4\pi} \frac{1}{m_\chi \tau_\chi} \left(\sum_F B_F \frac{dN_{\nu_i}^F}{dE} \right) R_\odot \rho_\odot \times J_1(\Delta\Omega) \quad (2)$$

for the case of decaying DM, where $R_\odot = 8.5$ kpc is the distance from the galactic center (GC) to the solar system, $\rho_\odot = 0.3$ GeV/cm³ is the DM density in the solar neighborhood, m_χ is the DM mass, τ_χ is the DM decay time and $dN_{\nu_i}^F/dE$ is the neutrino spectrum per annihilation or decay for a given annihilation or decay channel F with a corresponding branching fraction B_F . For $\chi\chi \rightarrow \nu\bar{\nu}$ channel, we assume that two neutrinos are produced per annihilated DM pair and all neutrino flavors are equally populated. Thus the neutrino spectrum per flavor is a monochromatic line with $dN_\nu/dE = \frac{2}{3}\delta(E - m_\chi)$. On the other hand, the neutrino spectrum per flavor for $\chi \rightarrow \nu\bar{\nu}$ channel is $dN_\nu/dE = \frac{2}{3}\delta(E - \frac{m_\chi}{2})$. The neutrino spectra $dN_{\nu_i}^F/dE$ for other channels are summarized in Refs [17, 27]. The quantity $\langle\sigma v\rangle$ is the thermally averaged annihilation cross section, which can be written as

$$\langle\sigma v\rangle = B\langle\sigma v\rangle_0, \quad (3)$$

with a boost factor B [28]. We set $\langle\sigma v\rangle_0 = 3 \times 10^{-26}$ cm³s⁻¹, which is the typical annihilation cross section for the present dark matter abundance under the standard thermal relic scenario [1]. We treat the boost factor B as a phenomenological parameter. The dimensionless quantity $J_n(\Delta\Omega)$ is the DM distribution integrated over the line-of-sight (l.o.s) and averaged over a solid angle $\Delta\Omega = 2\pi(1 - \cos\psi_{\max})$, i.e.,

$$J_n(\Delta\Omega) = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} d\Omega \int_{\text{l.o.s}} \frac{dl}{R_\odot} \left(\frac{\rho(r(l, \psi))}{\rho_\odot} \right)^n, \quad (4)$$

where ρ is the DM density at a specific location described by the coordinate (l, ψ) with l

TABLE I: Parameters of the density profiles for DM halo.

DM halo model	R_s in kpc	ρ_s in GeV/cm ³
NFW	20.0	0.260
Einasto	21.5	0.0538
Isothermal	3.50	2.07

the distance from the Earth to DM and ψ the direction of DM viewed from the Earth with $\psi = 0$ corresponding to the direction of GC. The distance $r \equiv \sqrt{R_\odot^2 + l^2 - 2R_\odot l \cos\psi}$ is the distance from GC to DM. We computed the values of $J_n(\Delta\Omega)$ with DarkSUSY [29]. For the galactic DM distribution, we consider Navarro-Frenk-White (NFW) [30], Einasto [31–33] and Isothermal profiles [34]. The functional forms of these profiles are given by

$$\rho_{\text{NFW}}(r) = \rho_s \frac{R_s}{r} \left(1 + \frac{r}{R_s}\right)^{-2}, \quad (5)$$

$$\rho_{\text{Ein}}(r) = \rho_s \times \exp \left\{ -\frac{2}{\alpha} \left[\left(\frac{r}{R_s} \right)^\alpha - 1 \right] \right\}, \quad \alpha = 0.17, \quad (6)$$

$$\rho_{\text{Iso}}(r) = \frac{\rho_s}{1 + (r/R_s)^2}, \quad (7)$$

with values of R_s and ρ_s given in Table I. In all cases we impose the normalization $\rho_\odot = 0.3 \text{ GeV/cm}^3$, which is at $r = 8.5 \text{ kpc}$. The comparison of different DM halo models is shown in Fig. 1.

Neutrinos are significantly mixed through oscillations when they travel a vast distance across the galaxy. The observed flavor ratio of DM induced neutrinos is related to the flavor ratio at the source through the probability matrix $P_{\alpha\beta} \equiv P(\nu_\beta \rightarrow \nu_\alpha)$ [35–37]. In particular, the exact form of $P_{\alpha\beta}$ in terms of mixing angles θ_{ij} and CP phase δ is given in Ref. [37]. The mixing angles θ_{23} and θ_{12} has been well measured while newest results for θ_{13} from accelerator [38] and reactor experiments [39–41] are also available. We take $\sin^2 \theta_{23} = 0.396$, $\sin^2 \theta_{12} = 0.307$, $\sin^2 \theta_{13} = 0.0241$ and $\delta = 1.08\pi$, which are best fit values of neutrino mixing

parameters from a recent global fitting [42] in the case of normal mass hierarchy. Therefore,

$$\begin{aligned}\Phi_{\nu_e} &= 0.55\Phi_{\nu_e}^0 + 0.24\Phi_{\nu_\mu}^0 + 0.21\Phi_{\nu_\tau}^0, \\ \Phi_{\nu_\mu} &= 0.24\Phi_{\nu_e}^0 + 0.40\Phi_{\nu_\mu}^0 + 0.36\Phi_{\nu_\tau}^0, \\ \Phi_{\nu_\tau} &= 0.21\Phi_{\nu_e}^0 + 0.36\Phi_{\nu_\mu}^0 + 0.43\Phi_{\nu_\tau}^0,\end{aligned}\tag{8}$$

where $\Phi_{\nu_i}^0$ and $\Phi_{\nu_{\nu_i}}$ are neutrino fluxes at the source and on the earth respectively. While the best fit neutrino mixing parameters differ slightly in the case of inverted mass hierarchy, they do not produce noticeable change in the above relation.

III. ATMOSPHERIC NEUTRINO FLUXES

We follow the approaches in [18, 43, 44] to compute the intrinsic atmospheric neutrino background fluxes. The ν_μ flux arising from π decays reads

$$\begin{aligned}\frac{d^2 N_{\nu_\mu}^\pi(E, \xi, X)}{dE dX} &= \int_E^\infty dE_N \int_E^{E_N} dE_\pi \frac{\Theta(E_\pi - \frac{E}{1-\gamma_\pi})}{d_\pi E_\pi (1-\gamma_\pi)} \\ &\times \int_0^X \frac{dX'}{\lambda_N} P_\pi(E_\pi, X, X') \frac{1}{E_\pi} F_{N\pi}(E_\pi, E_N) \\ &\times \exp\left(-\frac{X'}{\Lambda_N}\right) \phi_N(E_N),\end{aligned}\tag{9}$$

where E is the neutrino energy, X is the slant depth in units of g/cm^2 , ξ is the zenith angle in the direction of incident cosmic-ray nucleons, $r_\pi = m_\mu^2/m_\pi^2$, d_π is the pion decay length in units of g/cm^2 , λ_N is the nucleon interaction length while Λ_N is the corresponding nucleon attenuation length, and $\phi_N(E_N)$ is the primary cosmic-ray spectrum. We have $\phi_N(E_N) = \sum_A A \phi_A(E_N)$ with A the atomic number of each nucleus. The spectrum of each cosmic-ray component is parametrized by [45, 46]

$$\phi_A(E_N) = K \times (E_N + b \exp[-c\sqrt{E_N}])^{-\alpha},\tag{10}$$

in units of $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$. The fitting parameters α, K, b, c depend on the type of nucleus. They are tabulated in Ref. [46]. The function $P_\pi(E_\pi, X, X')$ is the probability that a charged pion produced at the slant depth X' survives to the depth X ($> X'$) [47]. $F_{N\pi}(E_\pi, E_N)$ is the normalized inclusive cross section for $N + \text{air} \rightarrow \pi^\pm + Y$, and is given in Ref. [43]. The kaon contribution to the atmospheric ν_μ flux has the same form as Eq. (9) with an inclusion of the branching ratio $B(K \rightarrow \mu\nu) = 0.635$ and appropriate replacements in kinematic factors as

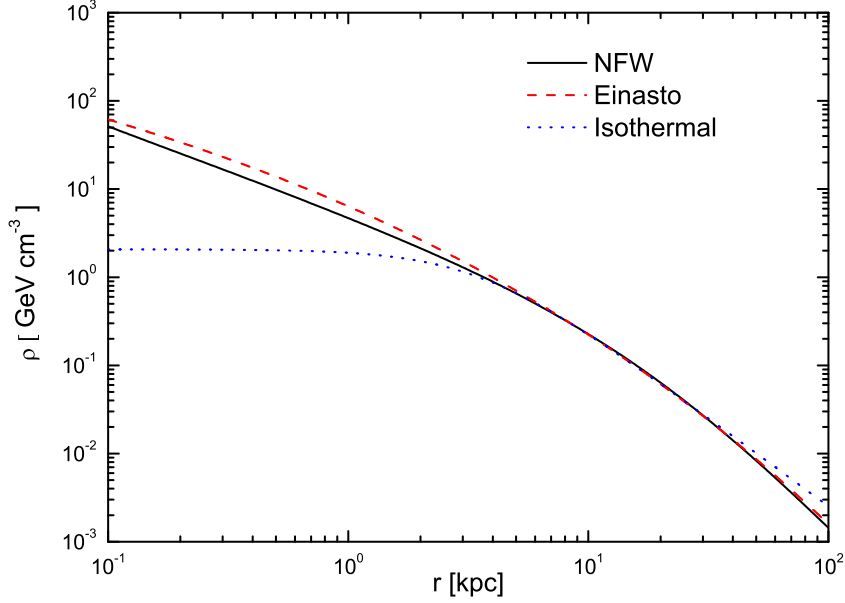


Fig. 1: Comparison of the dark matter density distribution, $\rho(r)$, as a function of distance from the Galactic Center as described by the NFW, Einasto and Isothermal halo models.

well as in the normalized inclusive cross section. The three-body muon decay contribution to the atmospheric ν_μ flux is also included. The details are discussed in Ref. [44]. After summing the two-body and three-body decay contributions, we obtain the total intrinsic atmospheric muon neutrino flux. From the Fig. 1 of Ref. [18], we note that angle-averaged atmospheric muon neutrino flux obtained by our calculation and that obtained by Honda et al. [48] both agree well with AMANDA-II results [49].

The intrinsic atmospheric ν_τ flux due to D_s decays can be obtained by solving cascade equations [44, 50]. One obtains

$$\frac{d^2 N_{\nu_\tau}(E, X)}{dE dX} = \frac{Z_{ND_s} Z_{D_s \nu_\tau}}{1 - Z_{NN}} \cdot \frac{\exp(-X/\Lambda_N) \phi_N(E_N)}{\Lambda_N}, \quad (11)$$

where $Z_{NN} \equiv 1 - \lambda_N/\Lambda_N$, Z_{ND_s} and $Z_{D_s \nu_\tau}$ are the Z moments defined in our previous work [18]. Finally, the atmospheric ν_μ flux taking into account the neutrino oscillation effect

is given by

$$\begin{aligned} \frac{d\bar{N}_{\nu_\mu}(E, \xi)}{dE} = \int dX \left[\frac{d^2 N_{\nu_\tau}}{dE dX} \cdot P_{\nu_\tau \rightarrow \nu_\mu} \right. \\ \left. + \frac{d^2 N_{\nu_\mu}}{dE dX} \cdot (1 - P_{\nu_\mu \rightarrow \nu_\tau}) \right], \end{aligned} \quad (12)$$

where $P_{\nu_\alpha \rightarrow \nu_\beta}$ is the $\nu_\alpha \rightarrow \nu_\beta$ oscillation probability. Sub-leading contributions to atmospheric ν_μ flux arising from $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_\mu$ oscillations are not included in the above equation. We can write down the atmospheric ν_τ flux in the similar way.

IV. RESULTS

In IceCube DeepCore, the track event rate for contained muons is given by

$$\Gamma_\mu = \int_{E_\mu^{\text{th}}}^{E_{\text{max}}} dE_\mu \int_{E_\mu}^{E_{\text{max}}} dE_{\nu_\mu} N_A \rho_{\text{ice}} V_{\text{tr}} \times \frac{d\Phi_{\nu_\mu}}{dE_{\nu_\mu}} \cdot \frac{d\sigma_{\nu N}^{\text{CC}}(E_{\nu_\mu}, E_\mu)}{dE_\mu} + (\nu \rightarrow \bar{\nu}), \quad (13)$$

while the cascade event rate is given by

$$\Gamma_{\text{casc}} = \int_{E_{sh}^{\text{th}}}^{E_{\text{max}}} dE_{sh} \int_{E_{sh}}^{E_{\text{max}}} dE_\nu N_A \rho_{\text{ice}} V_{\text{casc}} \times \frac{d\Phi_\nu}{dE_\nu} \cdot \frac{d\sigma_{\nu N}(E_\nu, E_{sh})}{dE_{sh}} + (\nu \rightarrow \bar{\nu}), \quad (14)$$

where $\rho_{\text{ice}} = 0.9 \text{ g cm}^{-3}$ is the density of ice, $N_A = 6.022 \times 10^{23} \text{ g}^{-1}$ is Avogadro's number, $V_{\text{tr}} \approx 0.04 \text{ km}^3$ is the effective volume of IceCube DeepCore array for muon track events [10, 15] and $V_{\text{casc}} \approx 0.02 \text{ km}^3$ is that for cascade events [15, 51], $d\Phi_\nu/dE_\nu$ is the neutrino flux arrived at IceCube, which is the sum of DM induced flux and the background atmospheric neutrino flux, E_{max} is taken as m_χ for annihilation and $m_\chi/2$ for decay, E_μ^{th} and E_{sh}^{th} are the threshold energies for track events and cascade events respectively, $d\sigma_{\nu N}^{\text{CC}}/dE_\mu$ is the differential cross section of neutrino-nucleon charged-current scattering, and $d\sigma_{\nu N}/dE_{sh}$ is the differential cross section for showers produced by neutrino-nucleon charged-current and neutral-current scatterings. In this work, we use differential cross sections $d\sigma_{\nu N}^{\text{CC}}/dE_\mu$ and $d\sigma_{\nu N}/dE_{sh}$ given by Ref. [52] with CTEQ6 parton distribution functions. The atmospheric part of $d\Phi_{\nu_e}/dE_{\nu_e}$ is taken from Ref. [48]. We also set $E_\mu^{\text{th}} = 10 \text{ GeV}$. It should be noted that the value for V_{tr} is an average effective volume based on the energy dependent V_{tr} discussed in Ref. [10], while the value for V_{casc} is just the instrumental volume of the DeepCore detector. The updated effective volumes of DeepCore detector for track and cascade events are available in Ref. [53]. While we adopt constant effective volumes for evaluating

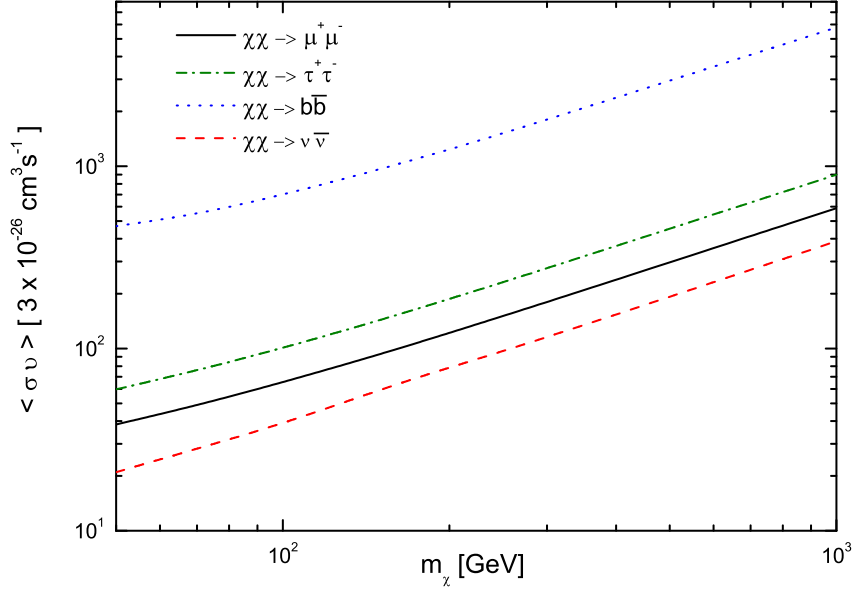


Fig. 2: The dotted line, dot-dashed line, solid line, and dashed line are the expected sensitivities on DM annihilation cross section by DeepCore detector for $\chi\chi \rightarrow b\bar{b}$, $\chi\chi \rightarrow \tau^+\tau^-$, $\chi\chi \rightarrow \mu^+\mu^-$, and $\chi\chi \rightarrow \nu\bar{\nu}$ channels, respectively.

DeepCore sensitivities, we shall also estimate how much the updated effective volumes affect our results.

As mentioned earlier, we consider neutrino fluxes generated through the annihilation channels $\chi\chi \rightarrow b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$ and $\nu\bar{\nu}$, and the decay channels $\chi \rightarrow b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$ and $\nu\bar{\nu}$. By computing the cascade event rates, we present in Fig. 2 the required DM annihilation cross section as a function of m_χ such that the neutrino signature from DM annihilations can be detected at the 2σ significance in five years. In this plot, we take NFW profile for DM density distribution in the galactic halo, the shower threshold energy $E_\mu^{\text{th}} = 10$ GeV and the cone half-angle $\psi_{\text{max}} = 50^\circ$. Non-detection of DM neutrino signature would then exclude the parameter region above the curve at the 2σ level. We have presented results corresponding to different annihilation channels. It is seen that the required annihilation cross section for 2σ detection significance is smallest for $\chi\chi \rightarrow \nu\bar{\nu}$ channel and largest for the channel $\chi\chi \rightarrow b\bar{b}$.

At this juncture, it is desirable to estimate effects of the updated effective volume on our sensitivity calculations. The energy dependent effective volume $V_{\text{casc}}(E)$ as given in Ref. [53] is roughly 3 times smaller than the value 0.02 km^3 adopted in our calculation for $E_\nu = 10 \text{ GeV}$. On the other hand, $V_{\text{casc}}(E)$ increases monotonically with energy with $V_{\text{casc}}(E)$ greater than 0.02 km^3 for $E_\nu > 40 \text{ GeV}$. For the annihilation process $\chi\chi \rightarrow \nu\bar{\nu}$, one has $E_\nu = m_\chi$. Hence the DeepCore sensitivity to this process should be better than that presented in Fig. 2, which starts from $m_\chi = 50 \text{ GeV}$. For $\chi\chi \rightarrow \mu^+\mu^-$ mode, $m_\chi = 50 \text{ GeV}$ corresponds to $E_\nu \simeq 20 \text{ GeV}$. At this energy, the value $V_{\text{casc}} = 0.02 \text{ km}^3$ overestimates the effective volume by about a factor of 2, thus the DeepCore sensitivity to $\langle\sigma(\chi\chi \rightarrow \mu^+\mu^-)v\rangle$ should be corrected by a factor of $\sqrt{2} \approx 1.4$. The correction factor gradually reduces to 1 as m_χ approaches to about 120 GeV , which corresponds to $E_\nu = 40 \text{ GeV}$. For $m_\chi > 120 \text{ GeV}$, the DeepCore sensitivity calculated with $V_{\text{casc}}(E)$ is better than that presented in Fig. 2. The correction factor for $\chi\chi \rightarrow \tau^+\tau^-$ is similar to that for $\chi\chi \rightarrow \mu^+\mu^-$. The hadronic mode $\chi\chi \rightarrow b\bar{b}$ requires different correction factor for the same m_χ . However we shall not address such a correction here since DeepCore detector is relatively insensitive to $\chi\chi \rightarrow b\bar{b}$.

Next, we show how the DeepCore sensitivity on DM annihilation cross section varies with the chosen cone half-angle and threshold energy for NFW DM density profile. Here we take $\chi\chi \rightarrow \mu^+\mu^-$ channel for illustration. Figure 3 shows the required DM annihilation cross section $\langle\sigma(\chi\chi \rightarrow \mu^+\mu^-)v\rangle$ for a 2σ detection in five years for different cone half-angle ψ_{max} . It is seen that the sensitivity is improved as ψ_{max} increases from 1° to 2° while it turns weaker as ψ_{max} increases further. In the latter case, the signal increases slower than the background does. In the same figure, we also show the result for a higher threshold energy $E_\mu^{\text{th}} = 50 \text{ GeV}$ with a cone half-angle $\psi_{\text{max}} = 10^\circ$ for comparison. This result is taken from Ref. [17] where $\psi_{\text{max}} = 10^\circ$ is identified as the most optimal cone half-angle for constraining DM annihilation cross section at that threshold energy. For large m_χ , lowering E_μ^{th} from 50 GeV to 10 GeV does not affect much the signal rate while increases significantly the atmospheric background event rate. Hence, the sensitivity on DM annihilation cross section becomes worse by choosing $E_\mu^{\text{th}} = 10 \text{ GeV}$. One expects the situation turns opposite for m_χ approaching to the threshold energy. In fact, for $m_\chi < 100 \text{ GeV}$, one can see that the sensitivity on DM annihilation cross section obtained with $E_\mu^{\text{th}} = 10 \text{ GeV}$ is always better than that obtained with $E_\mu^{\text{th}} = 50 \text{ GeV}$. We note that the DeepCore sensitivities on other annihilation channels have similar cone half-angle and threshold energy dependencies.

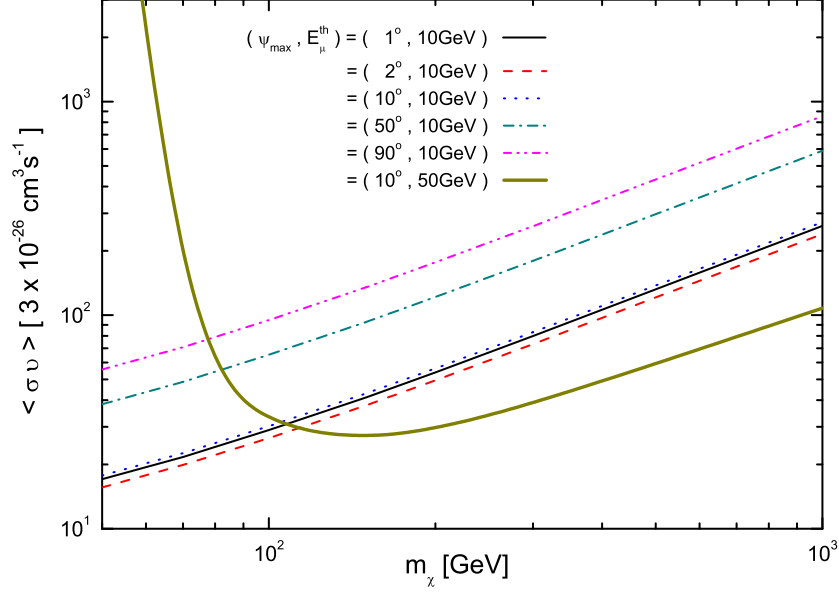


Fig. 3: The required DM annihilation cross section ($\chi\chi \rightarrow \mu^+\mu^-$) as a function of m_χ such that the cascade events induced by neutrinos from DM annihilations can be detected at the 2σ significance in five years. Results corresponding to different ψ_{max} are presented. For comparison, we also show the result with $E_\mu^{\text{th}} = 50$ GeV and $\psi_{\text{max}} = 10^\circ$ [17].

After discussing how the DeepCore sensitivities on DM annihilation cross section vary with the chosen cone half-angle and threshold energy for NFW profile, we study the variation of DeepCore sensitivities on $\chi\chi \rightarrow \mu^+\mu^-$ with ψ_{max} for different DM density profiles. First, we present in Fig. 4 our expected DeepCore sensitivities corresponding to different ψ_{max} for Einasto DM density profile. Similar to NFW profile, Einasto DM density distribution also has a cusp in the central DM region. We refer to this class of DM density profiles as the cusped profile. Therefore the DeepCore sensitivity on $\langle \sigma(\chi\chi \rightarrow \mu^+\mu^-)v \rangle$ with Einasto profile becomes poorer as ψ_{max} increases. In addition, we can see from Fig. 1 that the DM density of Einasto profile is higher than that of NFW profile between 0.1 kpc and 5 kpc from the GC, and both density profiles are almost identical beyond this range of distances. Hence the DeepCore sensitivity on $\langle \sigma(\chi\chi \rightarrow \mu^+\mu^-)v \rangle$ with Einasto profile is better than that with NFW profile for $\psi_{\text{max}} = 50^\circ$. Next, we also present in Fig. 4 the expected DeepCore

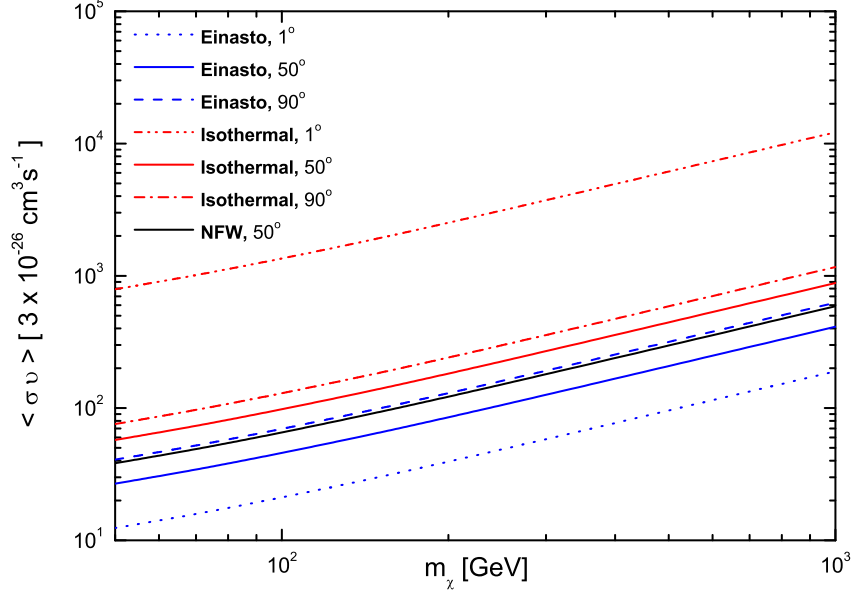


Fig. 4: The expected DeepCore sensitivities corresponding to different ψ_{max} for Einasto [31, 32], Isothermal [34] and NFW [30] DM density profiles.

sensitivities for different ψ_{max} with Isothermal DM density profile. Because there is a core in the central DM density distribution of Isothermal profile, we refer to this class of profile as the cored profile. We note that the sensitivity to DM annihilation cross section with Isothermal profile improves as ψ_{max} increases from 1° to 50° while the sensitivity with Einasto profile behaves oppositely. This is because that the DM density distribution of Isothermal profile maintains flat for a much longer distance from the GC as compared to the cusped profile. However, as ψ_{max} increases further, the DeepCore sensitivity to DM annihilation cross section becomes poorer even for Isothermal profile since the factor $J_2(\Delta\Omega)\Delta\Omega$ is proportional to the square of DM density. Finally, DeepCore sensitivities to DM annihilation cross section with Isothermal profile are poorer than those with cusped profiles for the same ψ_{max} . This results from the fact that DM densities of cusped profiles around GC are much larger than that of Isothermal profile in the same region.

In Fig. 5, we compare DeepCore sensitivities to DM annihilation cross section through measuring cascade events and track events. We note that ν_μ is the dominant flavor of atmo-

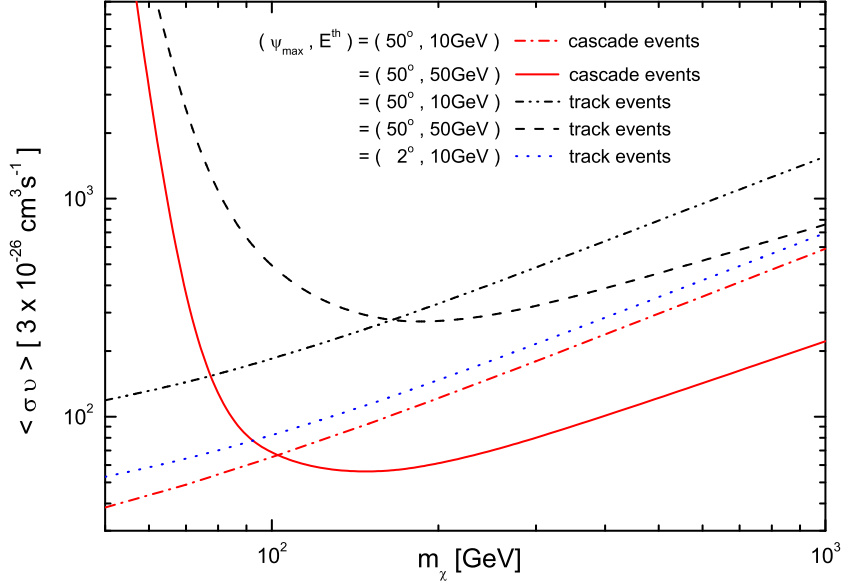


Fig. 5: The required DM annihilation cross section ($\chi\chi \rightarrow \mu^+\mu^-$) as a function of m_χ such that the neutrino signature from DM annihilations can be detected at the 2σ significance in five years for track and cascade events.

spheric neutrinos above few tens of GeV and the neutrino-nucleon cross section are almost the same for all flavors. Therefore, comparing with the result of track events, the signal to background ratio is enhanced in cascade events because ν_μ only produces the cascade events through the neutral-current interaction, which is lower in cross section than that of charged-current interaction. Hence cascade events in general provide better sensitivities to DM annihilation cross section than those provided by track events. However, we can see in Fig. 5 that the sensitivity curve of track events for $\psi_{\text{max}} = 2^\circ$ is close to that of cascade events. In other words, for DM annihilations, the sensitivity provided by track events with sufficiently small cone half-angle can be comparable to the sensitivity provided cascade events.

It is interesting and essential to compare our results with constraints obtained from gamma-ray astronomy and cosmology. Fermi large area telescope (Fermi-LAT) [54] is a pair-conversion telescope that explores the gamma-ray sky in the 20 MeV to 300 GeV range

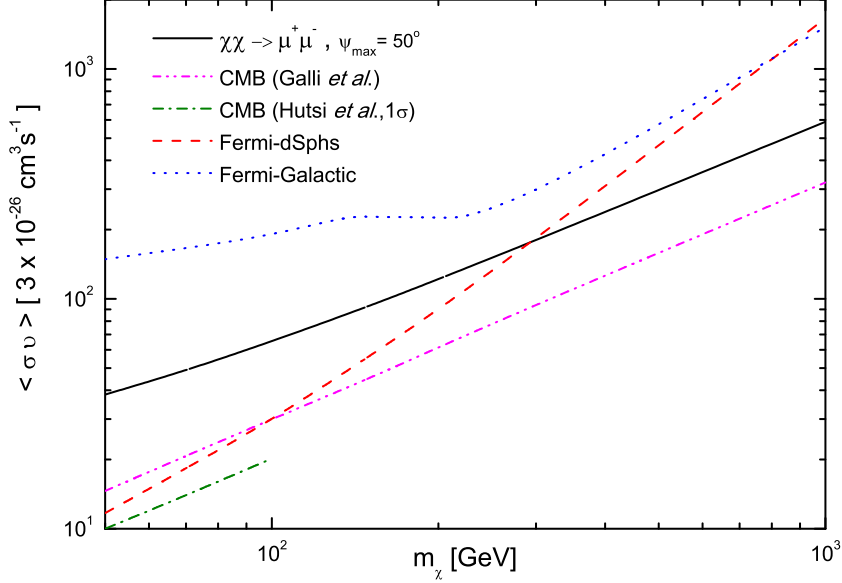


Fig. 6: Cross section limits on DM annihilation channel $\chi\chi \rightarrow \mu^+\mu^-$. The dot-dashed line is the 1σ upper bound on annihilation cross section for low-mass WIMP [22] obtained by WMAP7 data. The dot-dot-dashed line is the CMB constraint obtained by using WMAP7 + ACT data at 95% C.L. [23]. The dashed line is the dSphs constraint at 95% C.L. [20]. The dotted line is the constraint due to Fermi-LAT observations on the region $|b| > 10^\circ$ plus a $20^\circ \times 20^\circ$ square region centered at GC, assuming the NFW profile [19]. The solid line is our expected 2σ sensitivity with $E_\mu^{\text{th}} = 10$ GeV and $\psi_{\text{max}} = 50^\circ$.

with unprecedented sensitivity. In a recent work, Fermi-LAT collaboration derive constraints on WIMP annihilation or decay into various final states which produce a continuous photon spectrum [19]. These constraints are based upon the measured inclusive photon intensity spectrum from 4.8 GeV to 264 GeV obtained from two years of Fermi-LAT data over the region $|b| > 10^\circ$ plus a $20^\circ \times 20^\circ$ square region centered at GC with point sources removed. In Fig. 6, the dotted line is cross section upper limit on DM annihilation channel $\chi\chi \rightarrow \mu^+\mu^-$ from the diffuse gamma-ray spectrum with NFW profile. It is taken from Ref. [19] with a rescaling factor $(4/3)^2$ applied since we have adopted a local density of $\rho_\odot = 0.3$ GeV/cm³ while Fermi-LAT analysis uses $\rho_\odot = 0.4$ GeV/cm³. Our expected 2σ sensitivity on $\chi\chi \rightarrow$

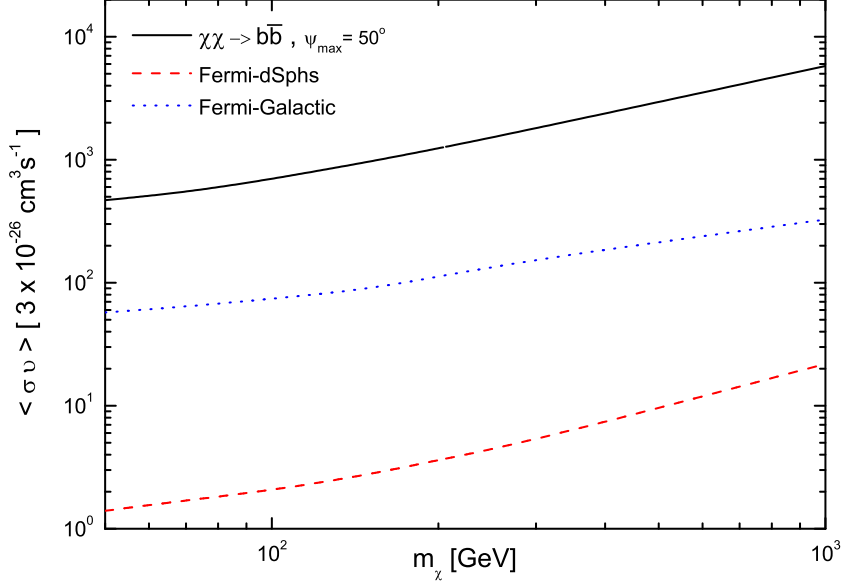


Fig. 7: Cross section limits on the DM annihilation channel $\chi\chi \rightarrow b\bar{b}$. The dashed line is the dSphs constraint at 95% C.L. [20]. The dotted line is the constraint due to Fermi-LAT observations for the region $|b| > 10^\circ$ plus a $20^\circ \times 20^\circ$ square region centered at the GC, assuming the NFW profile [19]. The solid line is our expected 2σ sensitivity with $E_\mu^{\text{th}} = 10$ GeV and $\psi_{\text{max}} = 50^\circ$.

$\mu^+\mu^-$ annihilation cross section by the DeepCore detector with $\psi_{\text{max}} = 50^\circ$ is plotted for comparison. We can see that our expected 2σ sensitivity with $\psi_{\text{max}} = 50^\circ$ is slightly stronger than this Fermi-LAT constraint, even if we calculate the sensitivity with $V_{\text{casc}}(E)$ given by Ref. [53].

Constraints on DM annihilation cross section were also obtained from cosmology and gamma-ray observations on dwarf spheroidal satellite galaxies (dSphs) of the Milky Way. Energy injection from DM annihilation at redshift $100 \lesssim z \lesssim 1000$ affects the CMB anisotropy. This is because the injected energy can ionize the thermal gas and modify the standard recombination history of the universe. The updated CMB constraints on DM annihilation cross sections are derived in Refs. [22] and [23], where the former work is based on the recent WMAP 7-year data [24] while the latter one combines WMAP 7-year and ACT 2008 [25] data. We present the above two CMB constraints on $\chi\chi \rightarrow \mu^+\mu^-$ annihilation cross sec-

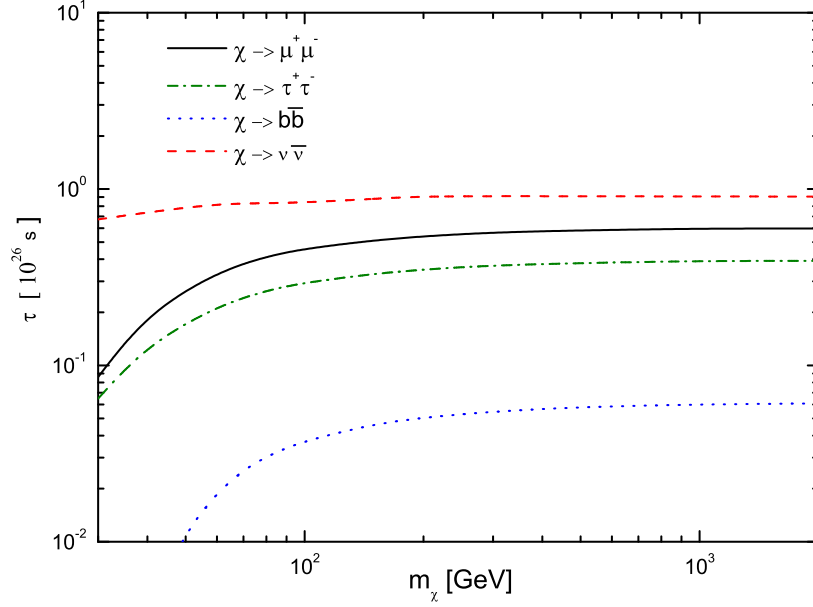


Fig. 8: The dotted line, the dot-dashed line, the solid line, and dashed line are the expected DeepCore sensitivities to DM decay time through cascade events from decay channels $\chi \rightarrow b\bar{b}$, $\chi \rightarrow \tau^+\tau^-$, $\chi \rightarrow \mu^+\mu^-$, and $\chi \rightarrow \nu\bar{\nu}$, respectively.

tion in Fig. 6. One can see that the solid line is higher than the dot-dot-dashed line (95% C.L.) by roughly a factor of 2. Thus our expected sensitivity is slightly weaker than the CMB constraint. However, it should be noted that the DM annihilation cross section could be velocity dependent. Hence, a model dependent extrapolation on DM annihilation cross section might be required to compare the constraint on $\langle\sigma v\rangle$ at redshift $100 \lesssim z \lesssim 1000$ to that at the present day universe [55].

Dwarf spheroidal satellite galaxies of the Milky Way are DM-dominated systems which do not have active star formation or detected gas content [56, 57]. Satellite galaxies are among the best targets to search for DM signals in gamma rays because of small background from astrophysical sources and a favorable signal to noise ratio. In Ref. [20], Fermi-LAT collaboration derive upper limits on DM annihilation cross sections by applying a joint likelihood analysis to 24 months of data from 10 satellite galaxies with uncertainties on the dark matter distributions in the satellite galaxies taken into account. We present the

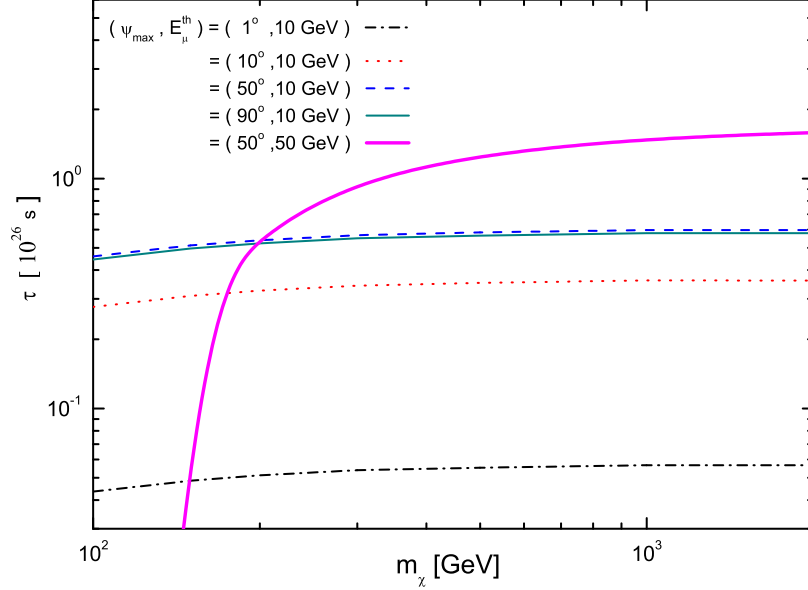


Fig. 9: The required DM decay time ($\chi \rightarrow \mu^+ \mu^-$) as a function of m_χ such that the neutrino signature from DM decays can be detected at the 2σ significance in five years for cascade events. Results corresponding to different ψ_{\max} are presented. For comparison, we also show the result with $E_\mu^{\text{th}} = 50$ GeV and $\psi_{\max} = 50^\circ$ [17].

dSphs constraint on $\chi\chi \rightarrow \mu^+ \mu^-$ annihilation cross section at 95% C.L. in Fig. 6. For $m_\chi > 300$ GeV, the expected DeepCore sensitivity curve is below that set by dSphs constraint. However, the dSphs constraint is stronger than the expected DeepCore sensitivity for $m_\chi < 300$ GeV, and even stronger than CMB constraint for $m_\chi < 100$ GeV.

We also present Fermi-LAT's dSphs constraint and galactic gamma ray constraint on $\chi\chi \rightarrow b\bar{b}$ annihilation cross section in Fig. 7. By comparing Figs. 6 and 7, we note that Fermi-LAT data gives more stringent constraint on $\chi\chi \rightarrow b\bar{b}$ mode than its constraint on $\chi\chi \rightarrow \mu^+ \mu^-$ mode. This is in contrast to the DeepCore case as one can see from Fig. 2. While the neutrino spectrum through $\chi\chi \rightarrow \mu^+ \mu^-$ is harder than that through $\chi\chi \rightarrow b\bar{b}$, the gamma ray spectra through the above annihilations behave differently. The gamma ray spectrum from $\chi\chi \rightarrow b\bar{b}$ dominates over that from $\chi\chi \rightarrow \mu^+ \mu^-$ for most of the range of $x = E_\gamma/m_\chi$ [58]. The expected 2σ sensitivity on $\chi\chi \rightarrow b\bar{b}$ channel by the DeepCore detector

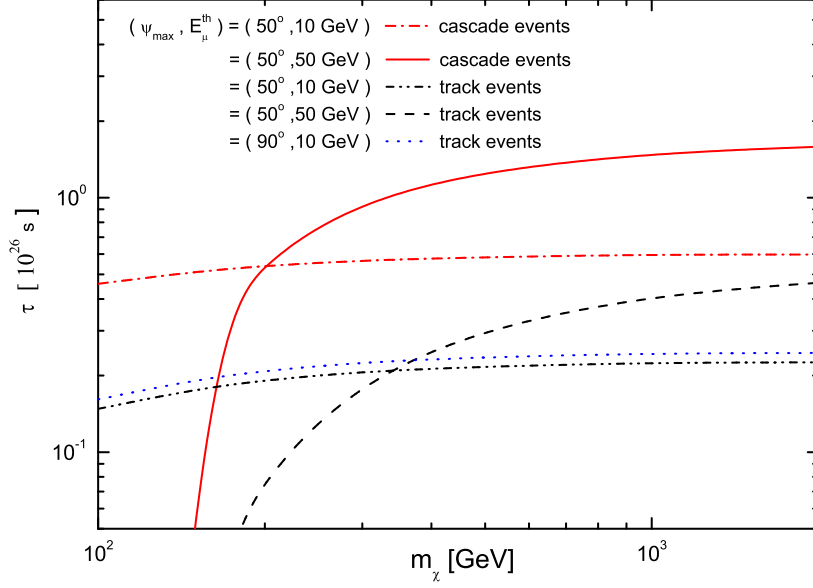


Fig. 10: The required DM decay time ($\chi \rightarrow \mu^+ \mu^-$) as a function of m_χ such that the neutrino signature from DM decays can be detected at the 2σ significance in five years for track and cascade events.

with $\psi_{\max} = 50^\circ$ is also shown in Fig. 7. One can see that the expected DeepCore sensitivity on this channel is weaker than all existing constraints presented here.

In addition to studying DeepCore sensitivities on DM annihilation channels, we also study sensitivities on DM decay time for $\chi \rightarrow b\bar{b}$, $\tau^+ \tau^-$, $\mu^+ \mu^-$ and $\nu \bar{\nu}$ channels. Figure 8 shows the required DM decay time for reaching 2σ detection significance in five years on cascade events from each channel with the threshold energy $E_\mu^{\text{th}} = 10$ GeV and a cone half-angle $\psi_{\max} = 50^\circ$. Non-detection of such a signature would then exclude the parameter region below the curve at the 2σ level. We can see that $\chi \rightarrow \nu \bar{\nu}$ channel requires the lowest decay rate (longest decay time) to reach the 2σ detection significance in five years of DeepCore data taking. We note that the energy-dependent effective volume $V_{\text{casc}}(E)$ [53] downgrades the sensitivity to $\chi \rightarrow \nu \bar{\nu}$ decay time by roughly a factor of 1.5 at $m_\chi = 30$ GeV, which corresponds to $E_\nu = 15$ GeV. However, the sensitivity to $\chi \rightarrow \nu \bar{\nu}$ obtained with $V_{\text{casc}}(E)$ is better than that presented in Fig. 8 for $m_\chi > 80$ GeV, which corresponds to $E_\nu > 40$ GeV.

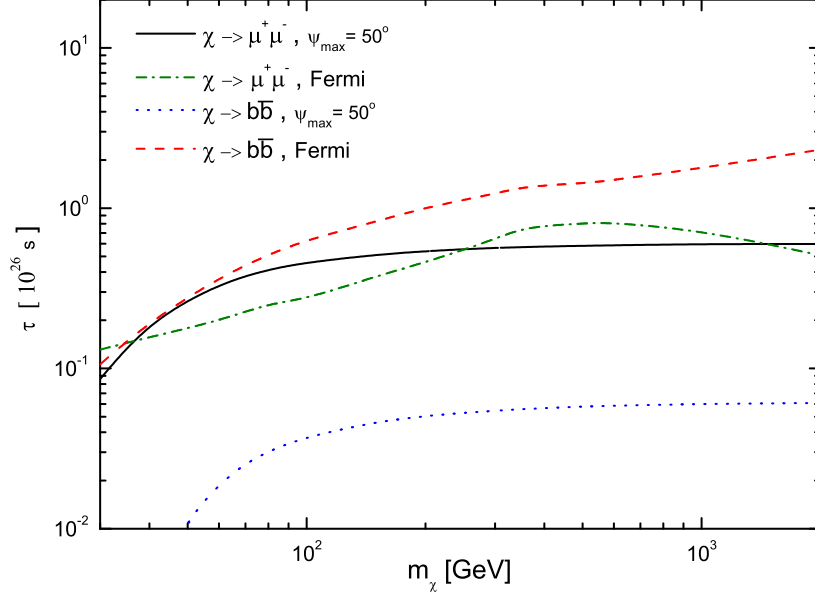


Fig. 11: The dot-dashed line and dashed line are the decay time constraints for $\chi \rightarrow \mu^+\mu^-$ and $\chi \rightarrow b\bar{b}$ channels due to Fermi observations for the region $|b| > 10^\circ$ plus a $20^\circ \times 20^\circ$ at GC, assuming the NFW profile [19]. The solid line and dotted line are our expected 2σ sensitivities for $\chi \rightarrow \mu^+\mu^-$ and $\chi \rightarrow b\bar{b}$ channels with $E_\mu^{\text{th}} = 10$ GeV and $\psi_{\text{max}} = 50^\circ$.

For $\chi \rightarrow \mu^+\mu^-$ mode, the sensitivity at $m_\chi = 30$ GeV is lower by a factor of $\sqrt{3} \approx 1.7$ by applying $V_{\text{casc}}(E)$, since such a m_χ corresponds to lowest possible neutrino energy $E_\nu = 10$ GeV. However, $V_{\text{casc}}(E)$ shall enhance the sensitivity for $m_\chi > 240$ GeV, which corresponds to $E_\nu = 40$ GeV, assuming $E_\nu \simeq m_\chi/6$. The correction factor for $\chi \rightarrow \tau^+\tau^-$ is similar to that for $\chi \rightarrow \mu^+\mu^-$, while the hadronic mode $\chi \rightarrow b\bar{b}$ requires different correction factor for the same m_χ . Once more, we do not address such a correction as the DeepCore detector is relatively insensitive to $\chi \rightarrow b\bar{b}$.

Next, we show how the DeepCore sensitivity on DM decay time varies with the chosen cone half-angle and threshold energy. We use $\chi \rightarrow \mu^+\mu^-$ channel to illustrate these effects. In Fig. 9, we present the required DM decay time ($\chi \rightarrow \mu^+\mu^-$) as a function of m_χ for reaching 2σ detection significance in five years for different cone half-angle ψ_{max} . The sensitivity curve rises as ψ_{max} increases from 1° to 50° . As ψ_{max} increases in this cone half-angle range, the

DM event rate increases faster than that of atmospheric background. However, the curve falls with an increasing ψ_{\max} for $\psi_{\max} > 50^\circ$, where the signal increases slower than the background does. We also show the required DM decay time for a 2σ detection significance in five years with $E_\mu^{\text{th}} = 50$ GeV and $\psi_{\max} = 50^\circ$ for comparison. It has been pointed out in Ref. [17] that $\psi_{\max} = 50^\circ$ gives rise to the highest sensitivity on DM decay time for $E_\mu^{\text{th}} = 50$ GeV. We note that the sensitivity on DM decay time is improved by lowering E_μ^{th} from 50 GeV to 10 GeV for $m_\chi < 200$ GeV.

It is of interest to compare sensitivities on DM decay time given by cascade events and track events. In Fig. 10, one can see that cascade events provide better sensitivity on DM decay time than that given by track events for the same E_μ^{th} and ψ_{\max} . In the same figure we also show the sensitivity given by track events for $\psi_{\max} = 90^\circ$. Such a ψ_{\max} renders the best sensitivity for track events. However this sensitivity is still poorer than those given by cascade events.

In Fig. 11, we present decay time lower limits for $\chi \rightarrow \mu^+\mu^-$ and $\chi \rightarrow b\bar{b}$ channels obtained from the diffuse gamma-ray spectrum for the region $|b| > 10^\circ$ plus a $20^\circ \times 20^\circ$ square region centered at GC, assuming the NFW profile. They are taken from Ref. [19], with a rescaling factor $3/4$ applied since we have adopted a local density of $\rho_\odot = 0.3$ GeV/cm³ while Fermi-LAT analysis uses $\rho_\odot = 0.4$ GeV/cm³. In the same figure, we also show the expected 2σ sensitivities to $\chi \rightarrow \mu^+\mu^-$ and $\chi \rightarrow b\bar{b}$ decay time by the DeepCore detector with $\psi_{\max} = 50^\circ$ for comparisons. For the DeepCore detector, the sensitivity to the $\chi \rightarrow \mu^+\mu^-$ decay time is better than that to the $\chi \rightarrow b\bar{b}$ decay time, since the neutrino spectrum in the former channel is harder than the one in the latter channel. On the other hand, the Fermi-LAT data in general gives more stringent constraint on $\chi \rightarrow b\bar{b}$ decay time than its constraint on the decay time of $\chi \rightarrow \mu^+\mu^-$. This is because that the gamma ray spectrum from the former channel dominates over the one from the latter channel for most of the range of $x = E_\gamma/m_\chi$, as the DM annihilation case. If DM decays predominantly into $\mu^+\mu^-$, one can see that the decay time sensitivity expected at DeepCore is comparable to the constraint given by Fermi-LAT data. This conclusion is not altered by adopting the energy-dependent effective volume $V_{\text{casc}}(E)$ [53]. On the other hand, if DM decays predominantly to $b\bar{b}$, the expected DeepCore sensitivity is much poorer than the constraint from Fermi-LAT data.

V. DISCUSSIONS AND CONCLUSIONS

In this paper, we have evaluated sensitivities of IceCube DeepCore detector to neutrino cascade events induced by DM annihilations and decays in galactic halo. We focus on the scenario of small DM mass and the threshold energy for the cascade events is taken to be 10 GeV. The event rate of background atmospheric neutrinos is calculated with $\nu_\mu \rightarrow \nu_\tau$ oscillations taken into account for neutrino energies less than 40 GeV. The signal event rate is calculated by taking NFW profile for DM density distribution in the galactic halo. Among all DM annihilation and decay channels, the annihilation mode $\chi\chi \rightarrow \nu\bar{\nu}$ and the decay mode $\chi \rightarrow \nu\bar{\nu}$ provide the best search sensitivity, while the search sensitivity provided by the annihilation mode $\chi\chi \rightarrow b\bar{b}$ and the decay mode $\chi \rightarrow b\bar{b}$ is the poorest.

It is important to compare the expected sensitivities of DeepCore detector to DM annihilation cross section and decay time with the existing constraints on the same quantities obtained by cosmology and Fermi-LAT gamma-ray observations. It is seen that the Fermi-LAT constraints on $\chi\chi \rightarrow b\bar{b}$ and $\chi \rightarrow b\bar{b}$ are much stronger than the expected DeepCore sensitivities to the same channels. Hence, if DM predominantly annihilates or decays into $b\bar{b}$, the DeepCore detector is not expected to observe neutrino signature induced by DM in the galactic halo. For leptonic final states, one can see from Fig. 6 that the expected DeepCore sensitivity to $\chi\chi \rightarrow \mu^+\mu^-$ annihilation cross section is slightly stronger than the Fermi-LAT constraint on the same channel based upon gamma-ray data from the galactic halo. However, the former is slightly weaker than both the dSphs constraint and the constraint obtained from WMAP and ACT results on CMB anisotropy. In Fig. 11, we also see that the expected DeepCore sensitivity to $\chi \rightarrow \mu^+\mu^-$ decay time is comparable to the Fermi-LAT constraint based upon gamma-ray data from the galactic halo. From the above comparisons, there are still slight possibilities to observe DM induced neutrino signature from the galactic halo provided DM annihilates or decays predominantly into leptons.

It should be noted that Fermi-LAT and CMB data does not directly set limits on $\chi\chi \rightarrow \nu\bar{\nu}$ or $\chi \rightarrow \nu\bar{\nu}$ modes with monochromatic neutrinos. There exist models [59, 60] in which $\chi\chi \rightarrow \nu\bar{\nu}$ and $\chi \rightarrow \nu\bar{\nu}$ are dominant annihilation and decay modes, respectively. In the annihilation case [59] for example, the DM candidate can be the lightest right-handed (RH) sneutrino in a $U(1)_{B-L}$ extension of the minimal supersymmetric standard model. RH sneutrinos annihilate into a pair of RH neutrinos. Each of these RH neutrinos then decays

into ordinary left-handed (LH) neutrino and a neutral Higgs boson while the decay of RH neutrino into charged final states $l^\pm h^\mp$ is typically forbidden in such a model. In the case that the mass difference between RH sneutrinos and RH neutrinos is small, RH neutrinos are produced non-relativistically by DM annihilations. Hence LH neutrinos produced by the decays of RH neutrinos are approximately monochromatic with an energy around half of the DM mass. Hence the sensitivity of IceCube DeepCore to this type of models can be read off from the $\chi\chi \rightarrow \nu\bar{\nu}$ curve in Fig. 2 with the shift $(\langle\sigma v\rangle, m_\chi) \rightarrow (\langle\sigma v\rangle, 2m_\chi)$.

We like to stress that neutrino signatures induced by DM in the galactic halo can be more easily detected by neutrino telescope in northern hemisphere. The effective area for track events in KM3NeT as a function of neutrino energy has been estimated [61]. With this effective area, we also calculate the sensitivity of KM3NeT to DM annihilation cross section $\langle\sigma(\chi\chi \rightarrow \mu^+\mu^-)v\rangle$ in the galactic halo. For $\psi_{\max} = 10^\circ$ and $m_\chi = 200$ GeV, the KM3NeT 2σ sensitivity to $\langle\sigma(\chi\chi \rightarrow \mu^+\mu^-)v\rangle$ in 5 years is comparable to the CMB constraint on this channel [23]. However, for $m_\chi = 1$ TeV, CMB constraint gives $\langle\sigma(\chi\chi \rightarrow \mu^+\mu^-)v\rangle$ no greater than $10^{-23} \text{ cm}^3\text{s}^{-1}$ whereas the KM3NeT 2σ sensitivity on the same annihilation channel can reach to $1.5 \times 10^{-24} \text{ cm}^3\text{s}^{-1}$ in 5 years.

In conclusion, we have made detailed comparisons between IceCube DeepCore sensitivities and other existing constraints on various DM annihilation and decay channels. The prospect for DeepCore detector to observe neutrino signature induced by DM in the galactic halo has been discussed. We have also mentioned the possible improvement by KM3NeT on this observation.

Acknowledgments

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